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Abstract

The X-31 Enhanced Fighter Maneuverability Program has been reorganized to form the International Test Organization, with the NASA Dryden Flight Research Facility (NASA-Dryden) as the responsible test organization. The two X-31 research aircraft and engineering support personnel have been colocated at NASA-Dryden, with flight test operations beginning in April 1992. Therefore rapid development of a hardware-in-the-loop simulation was needed to support the flight test operations at NASA-Dryden, and to perform verification and validation of flight control software. This paper will discuss the X-31 simulation system requirements, distributed simulation system architecture, simulation components from math models to the visual system, and the advanced capabilities the X-31 simulation provides. In addition, unique software tools and the methods used to rapidly develop this simulation system will be highlighted.

Nomenclature

CAST	computer-aided system test
CIU	cockpit interface unit
DAC	digital analog converter
DDI	digital display unit (a cockpit display unit)
FCC	flight control computer
FCS	flight control system
FHILS	flight hardware-in-the-loop simulation
HUD	heads-up display
INU	inertial navigation unit
I/O	input/output
ITF	Integrated Test Facility
MBB	Messerschmitt-Bolkow-Blohm
RTADS	real-time all-digital simulation
SES	simulation electric stick
STE	system test equipment
UMN	Universal Memory Network™
VME	Versa-Module Eurocard
3-D	three dimensional

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Introduction

The X-31 Enhanced Fighter Maneuverability Program has been reorganized to form the International Test Organization, with the NASA Dryden Flight Research Facility (NASA-Dryden) as the responsible test organization. The X-31 International Test Organization is comprised of personnel from the United States and Germany. The organizations from the United States include the Defense Agency Research Projects Agency (DARPA), NASA-Dryden, the Air Force, Navy, and Rockwell International Corp., and its subcontractors. The German organizations include the German Ministry of Defense and Messerschmitt-Bolkow-Blohm (MBB). Flight-testing of two X-31 research aircraft will demonstrate the tactical utility of enhanced fighter maneuverability.[1] Figure 1 shows the X-31 Enhanced Fighter Maneuverability vehicle.

The simulation system and research aircraft are recent additions to the NASA-Dryden Integrated Test

Facility (ITF). The ITF was built specifically to support the ground- and flight-testing of advanced research aircraft employing digital flight control systems (FCSs).[2] The ITF colocates the research aircraft, flight simulations, and the engineering and aircraft technicians for the program.

The rapid development of the X-31 simulation at NASA-Dryden was possible through the efforts of three primary groups: the Rockwell International Corp. simulation team, the MBB flight control engineers, and the NASA-Dryden ITF simulation team. Together they form the X-31 simulation team. The Rockwell simulation team provided all simulation models including aerodynamics, propulsion, and gear models and assisted in implementing the hardware-in-the-loop simulation. Messerschmitt-Bolkow-Blohm personnel provided computer models of the aircraft's control laws for the batch and real-time all-digital versions of the simulation—the versions which do not use the FCS hardware. The NASA-Dryden ITF simulation team implemented the simulation models and integrated the control laws in batch, all-digital and flight hardware-in-the-loop simulations. In addition to hosting the simulation models, the ITF simulation team evaluated and selected a computer platform for the simulation, and assisted in defining a new hardware-in-the-loop interface to the quad-redundant flight control computers (FCCs). The ITF simulation team also designed and developed the cockpit, computer-aided system test (CAST) tools, and visual systems.

The following sections of the paper will discuss the general X-31 simulation requirements and provide an overview of the distributed simulation system architecture. The key components of the simulation system are the simulation computer, simulation modeling, interfaces to the flight hardware, the simulation cockpit, the CAST software tools used to automate the verification and validation of the flight control software, and finally, the visual system. The unique software tools and methods used to rapidly develop the simulation system also will be discussed.

The use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

General X-31 Simulation Requirements

The general X-31 simulation requirements include the requirement to support flight test operations and flight control software verification and validation using a FCS hardware-in-the-loop simulation configuration. Flight test operations require the use of simulation for pilot training, flight test planning, and engineering analysis. Onsite simulation provides engineers with immediate access to the engineering tools they need. This arrangement benefits engineers from the areas of flight control, flight systems, propulsion, and other disciplines. Other requirements to support flight test operations fall into three main areas: matching the cockpit layout, simulation model fidelity, and visual displays.

Flight control verification and validation requirements include automation of the flight software test process and the need for batch, real-time all-digital and hardware-in-the-loop simulations. Automating the software verification and validation process requires the integration of the existing open-loop verification techniques[3] with the closed-loop NASA-Dryden CAST validation tools. Three versions of the simulation are used to design, evaluate, and test FCS changes. Typically, the batch simulation is used to design FCS changes, then the real-time all-digital simulation (RTADS) allows for piloted and engineering evaluations. Once a change is approved and implemented, the hardware-in-the-loop simulation is used to test, verify, and validate the change before flight. The hardware-in-the-loop simulation requires real-time, low data latency interfaces with the FCS computers. Low data latency minimizes phase lag and assures that the simulation matches the vehicle's in-flight responses.

Simulation Architecture

Advances in computer processing and graphics technology are reshaping the simulation market, driving it toward smaller, low-cost simulations.[4] The architecture for the X-31 simulation is based on this advanced computer technology, using high-performance Unix-based workstations and Versa-Module Eurocard (VME) systems connected through a shared-memory network. Figure 2 shows the main components of the simulation system and the connections through the shared-memory network. The shared-memory network, called the Universal Memory Network™ (UMN), was developed for NASA by the Computer Sciences Corp., El Segundo, California, to allow different computer systems to communicate at memory speeds.

The simulation architecture has been developed at NASA-Dryden over many years, in an effort to meet the requirements for low data latency in flight hardware-in-the-loop simulations (FHILS). As discussed in detail in the following section, the simulation/visual system and CAST tools are hosted on Silicon Graphics, (Mountain View, California) Power Series 4D-440 computers with the VGX graphics option. The data recording system is hosted on an Encore Series 32/67 computer (Encore Computer Corp., Fort Lauderdale, Florida). It records and time-tags simulation calculations, cockpit parameters, and flight hardware data at rates up to 570,000 parameters/sec. The interface systems for the cockpit, the MIL-STD-1553B data ingest for data monitoring, and the flight hardware are VME-based. A key feature of the simulation architecture is the ability of all computers to communicate without any processor overhead by simply reading/writing directly to memory.

Discussion of Simulation Components

The following sections will provide some insight into the specific design requirements, design approaches, and tools used to rapidly develop and integrate the components into the X-31 simulation.

Simulation Computer Selection

Initial evaluations of the X-31 simulation modeling and real-time requirements indicated that current ITF simulation computers were unable to model the vehicle at the required iteration rate. The X-31 simulation required a faster simulation computer. A set of technical and managerial requirements were generated and vendors were invited to test their systems against the matrix of requirements for the computer selection process. The following table lists the technical and managerial requirements and the evaluation process used to determine the vendor's ability to meet the requirement.

Simulation requirement matrix.

Requirement	Evaluation process
Computational performance; three-times improvement over existing capability	Benchmarks of NASA-Dryden simulations
Context switch time (interrupt response time) no greater than 200 μsec	Actual timing of context switch time
Minimum effort to convert existing simulations, less than 1 workweek	Port F-18 batch simulation, evaluate use of shared common blocks
Must be compatible with existing hardware interfaces, EtherNet®, VME, cockpits, etc.	Documentation review
IEEE 754 standard floating point format	Documentation and simulation benchmarks
Must comply with government and industry standard operating systems	Documentation and simulation benchmarks
Mature software development environment; must support FORTRAN, Ada, and C languages	Evaluation of compilers, debuggers, help features, and ability to interface code written in different languages
Must support X Window System™ environment	Ability to port CAST software
25-percent expansion beyond baseline system	Evaluate multiple processor systems, documentation, and benchmarks
Maintainability and supportability, 24-hr response time	Vendor response and documentation
Simulation computer cost: less than $200,000	Costs to implement X-31 configuration

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™ X Window System is a trademark of Massachusetts Institute of Technology, Cambridge, Massachusetts.

Each vendor's system was evaluated and scored for each of the categories in the table. Nearly all vendors offered a low-cost, Unix-based system, which indicates the direction the simulation market is taking. The Silicon Graphics Power Series 4D-440 with the VGX graphics option was selected for the X-31 simulation. The Silicon Graphics Power Series 4D-440 led the field in most of the criteria and with the integral graphics for visual scene generation; it also represented the lowest overall cost.

The ability of a Unix-based workstation to meet the real-time simulation requirements is significant. The larger Unix market offers much lower costs than the specialized real-time computer market. The larger workstation market also provides better third-party products and support services.

Simulation Model Integration

For NASA personnel to provide safety of flight assurance during flight-testing,[5] an X-31 simulation capability was required on site at NASA-Dryden. The flight controls engineers requested a batch mode simulation for offline analysis, RTADS, and FHILS. The RTADS and FHILS are real-time simulations which provide a pilot-in-the-loop capability. A real-time all-digital dome simulation was also retained at Rockwell to support program goals and offsite engineering analysis. In general, the same models are used in all versions of the simulation except the FHILS, which uses hardware actuator models and the aircraft FCCs for the control laws. The unique characteristics of the FHILS will be discussed in the following section.

The initial focus of the development process was to quickly establish a batch simulation capability at NASA-Dryden. The models that had been developed by Rockwell and MBB personnel were transferred on magnetic tape to NASA-Dryden. The X-31 simulation models included an aerodynamic model with rotary balance terms and flex-to-rigid ratios, an engine model, a software actuator model with hinge moments, a hydraulics model, a landing gear model, a weight/center of gravity/inertia model, and the control laws with a sensor model. Rockwell personnel provided the latest version of their RTADS source code, and MBB personnel provided a version of the X-31 control system code programmed in FORTRAN. Rockwell personnel also provided American Standard Code for Information Interchange (ASCII) versions of the simulation database. An electronic data transfer (Internet®) connection was established between the Rockwell site in Downey, California and NASA-Dryden so that updated source code and checkcases could be quickly transferred.

The NASA-Dryden X-31 batch simulation was developed on the Sun Microsystems SPARC® 1+ workstation (Mountain View, California). The simulation models were recoded in FORTRAN, which is the language of choice for NASA-Dryden simulation engineers. Routines to read-in the various simulation data tables were written as soon as the data were received. NASA-Dryden variable naming convention was maintained where possible. One important element that was missing was the table look-up routines for the aerodynamic database, which includes over 225,000 data points and more than 200 dependent variables. Some of the aerodynamic model coefficients are functions of up to five independent variables. To create the table look-up code, the NASA-Dryden Look-Up Code Generator was utilized. The Look-Up Code Generator is an in-house program used primarily for simulation development. This program uses two input files, which specify the variable dependencies and breakpoint structure and then create the source code required for the interpolation routines. The table look-up code was created and verified in only 2 workweeks. The verification process was greatly facilitated by X-Plot, a CAST plotting analysis tool. X-Plot was used to rapidly produce data plots that could be compared with hard copy plots provided by Rockwell personnel, thus verifying the correct implementation of the data tables.

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After completing the table look-up code, the X-31 simulation models were integrated into the standard NASA-Dryden simulation skeleton which includes the aircraft equations of motion and a unique user display interface. At this point the simulation verification process began. Rockwell personnel provided checkcases, which included pilot pulses and doublets from the RTADS. The checkcase signals were overplotted with the NASA-Dryden simulation results using X-Plot. Both X-Plot and the simulation have command file capabilities which allow these programs to read commands from an input file instead of the keyboard. Therefore, once the command files were created, they could be reused each time the simulation code or data were changed. These command files were used frequently during the debugging process. While the simulation command file was creating new checkcase data, the X-Plot command file was overplotting the previous checkcase data for analysis, thus allowing the simulation to be verified quickly.

The X-31 simulation development is significant because it was the first NASA-Dryden aircraft simulation developed solely on a machine with a Unix-based operating system. This greatly facilitated the simulation development process. The file hierarchy structure allowed the simulation source code to be organized coherently. In addition, Unix-based makefiles speeded up the compilation procedures. Unix-based utilities such as "grep" were used to find key simulation parameters in multiple source files. The "grep" utility was extremely useful to quickly organize and coordinate the transfer of the simulation models from the Rockwell and MBB formats to the NASA-Dryden simulation structure. The Sun SPARC 1+ workstation also provides an X-Window interface, which allows the user to run several programs concurrently in the multiwindow environment.

The X-31 batch simulation was reproduced at NASA-Dryden in less than 3 months. The simulation development and analysis tools, including the Look-Up Code Generator, X-Plot, and the command file capability, as well as the Unix-based operating system, greatly increased the development pace.

The next step in the development process was to provide the simulation with a real-time capability and pilot interface. First, the batch simulation was ported to the newly-acquired Silicon Graphics 4D-440 computer. Interrupt handler routines were written in C language to drive the real-time loop of the simulation with the internal clock. For simulation development prior to the finished construction of the fixed-base X-31 cockpit, an X-Window pilot interface was programmed using the CAST graphical user interface subroutines. This X-Window cockpit allowed the X-31 simulation to be flown and tested using the keyboard mouse to control the stick, rudder pedals, throttle, and various cockpit discretes. The simulation X-Window displays used during development are shown in Fig. 3. The X-Window cockpit is in the lower right corner. Once the actual cockpit was complete, the software pointers to the cockpit input/output (I/O) arrays were switched to use the cockpit interface unit (CIU) arrays in the UMN instead of the X-Window cockpit arrays in local shared memory.

With the X-31 cockpit complete and connected to the simulation through the CIU, the NASA-Dryden RTADS was ready, except for the software to drive the digital display indicator (DDI). The X-31 FCCs normally drive the cockpit DDI through a MIL-STD-1553B connection. However, the RTADS has the control laws programmed in software and therefore must emulate this function. Rockwell personnel provided the DDI download and update code, which was programmed in FORTRAN. This code was ported to the simulation computer and implemented as a subroutine. A MIL-STD-1553B board was added to the backplane of the simulation computer to connect the DDI. Routines were written in C language to read and write the DDI information through the MIL-STD-1553B connection.

The RTADS was verified using the Rockwell checkcases, as well as additional checkcases produced with the NASA-Dryden batch simulation. The RTADS was completed in just 6 months, and once operational, attention was focused on integrating the FCCs and the system test equipment (STE) with the simulation computer for the FHILS. This interface is described in the following section.

Flight Hardware-in-the-Loop Interface to the Real-Time Simulation

To preserve the integrity of the simulation, data latency between the simulation and FCCs must be minimal. Data latency increases phase lag, which can cause closed-loop instabilities. Toward this end, flight control engineers required that the simulation and FCCs housed in the STE be synchronized. The STE was built at Honeywell Inc. in Albuquerque, New Mexico and it provides the required I/O interfaces to the FCCs. The FCCs run at 50 Hz while the STE program, which performs the I/O operations between the FCCs and the simulation computer, runs at 100 Hz. The NASA-Dryden simulation also uses a frame rate of 100 Hz.

To satisfy the synchronization requirement, some minor changes were made to the FCC software. A discrete output was used to provide a synchronization pulse to the STE program. There were a number of spare discretes available in the FCCs, and one of these was designated as the synchronization discrete. The FCC software was modified to set the synchronization discrete true immediately following the FCC clock interrupt. The synchronization discrete is reset by the FCCs after the control system calculations have been performed, which is approximately 13 msec into the 20-msec FCC frame. The four FCCs were modified to output the synchronization discrete. In addition to maintaining commonality, this would allow the simulation to operate with one or more of the FCCs failed, or with only one FCC present in the STE.

The STE hardware and software were also modified to fulfill the synchronization requirement. The interface of the STE to the Rockwell simulation host computer was replaced with a VME interface to the UMN. This allowed direct data transfers between the VME-based STE and the simulation computer, and took advantage of the high-speed UMN connection. The STE program was modified to detect the synchronization pulse from the FCCs and to use it to synchronize with the simulation computer.

The synchronization scheme is shown in Fig. 4. The STE program detects the leading edge of the FCC synchronization pulse, which occurs less than 1 msec into the 20-msec FCC frame. The STE then reads the analog surface positions and writes them into the UMN, beginning the real-time loop. At this point, the STE program sets a flag in the UMN which instructs the simulation to input the surface positions and to perform the aircraft equations of motion. After the new aircraft states have been determined, the simulation outputs the new states and current pilot commands to the UMN, and synchronizes with the STE via a software flag. The STE then reads this information from the UMN and passes it to the FCCs. The STE and simulation program are synchronized every 10 msec as described previously. However, the STE only looks for the synchronization pulse from the FCCs on odd-numbered frames. The overall synchronization scheme is repeated every 20-msec FCC frame.

The FHILS is used primarily to verify and validate flight control system (FCS) software changes needed for flight-testing. The synchronized techniques provide minimal data latency, and resulted in a simulation that best matches the real aircraft in flight.

Cockpit Design

The goal of the X-31 cockpit and interface design is to provide a station for pilot training, mission planning, and engineering analysis. Meeting this goal requires that the cockpit be correct in appearance and feel. The simulation cockpit interface requires a data link between the simulation computer and the simulation cockpit instrumentation. Cockpit instrumentation includes a control stick, rudder pedals, throttle quadrant, instruments, lights, and switches. Strip charts are located next to the cockpit and are driven by the CIU.

The design approach for rapidly developing the X-31 cockpit and interfaces was to use commercially available components and previously developed hardware and software to minimize time and costs.

The cockpit shell used in the X-31 simulation is a T-26 simulation trainer cockpit, modified internally to resemble the actual X-31 cockpit, Fig. 5. An F-18 instrument panel has been used as the basis for the simulation instrument panel, just as in the X-31 aircraft. An F-18 stick grip and throttle quadrant were used in the cockpit. The availability of the cockpit shell and the F-18 equipment was critical to the rapid development of the X-31 simulation. The control stick and rudder pedal assembly is a NASA-Dryden-designed, general-purpose all-electric system. The auxiliary FCS panel, which provides flight control trim functions and deceleration mode switching, was fabricated using lights and switches that are commercially available. The simulation control panel, a NASA-Dryden-designed device that allows for the setting of initial conditions and for controlling simulation operation, was fabricated using commercially available parts. The analog instruments, lights, and switches that are used in the instrument panel are also commercially available parts. The DDI and the heads-up display (HUD) were supplied by the U.S. Navy.

The simulation interface to the cockpit must support two configurations. The first configuration, RTADS, does not use the FCCs in the loop. The second configuration, FHILS, incorporates the STE, which interfaces the FCC to the simulation for closed-loop evaluations. The flutter-test box, a device used to control the flutter excitation system, and the status test panel, a device used to display messages from the FCC, are available only in the FHILS configuration. By using a selector switch, the DDI/HUD combination can be driven through either the simulated MIL-STD-1553B data in the RTADS configuration or from the FCCs in the FHILS configuration. The FCS panel, a device that is used to perform special FCS and flight test functions, including the ability to change the FCS mode of operation, is switchable between both configurations. All other instrumentation can be used in both configurations. The overall block diagram for the X-31 cockpit and interface is shown in Fig. 6.

The CIU is a VME-based single-board computer that serves as the I/O controller. The CIU provides data communication between the simulation computer and the simulation cockpit, including pilot inputs. This communication is accomplished through the Universal Memory Network (UMN), a shared-memory network. The CIU is capable of data format conversion, configurable channel scaling and biasing, and real-time data collection and preprocessing.

The VME interface and protection unit (VIPR) receives the input and output signals from the CIU, performing buffering and any needed signal conditioning. The VIPR then distributes power and signal lines to the various X-31 simulation cockpit instruments.

The X-31 simulation cockpit and interface are of an open system design that allows for rapid reconfiguration and future expansion. The VME architecture of the CIU allows for future expansion using several commercially available I/O circuit cards. The VIPR allows for rapid reconfiguration of the power and signals to the cockpit instrumentation. This design has proven to be effective in several programs at NASA-Dryden, including the National Aero-Space Plane simulation.

Computer-Aided System Test Capabilities

The X-31 program requires quick turnaround time for FCS verification and validation. The CAST tools, combined with the X-31 open-loop test methods,[3] enable the X-31 project personnel to complete FCS verification and validation rapidly by automating the entire test process. The automation of the test process includes test setup, data recording, real-time display, analysis, and plotting. Figure 7 shows several CAST tools.

The CAST applications operate on a Unix-based workstation with an X-Window user interface. The X-Window approach is the reason for the X in each tool's name. The CAST applications acquire data through the UMN. Each step of the test process has one or more CAST tools available to help automate the testing. Test setup is primarily automated through the use of command files, discussed in the Simulation Model Integration section. During test operations several CAST tools are used. They include X-Aircraft Interrogation and Display System, X-Monitor, X-Capture, and X-Local Recording Capability. X-Aircraft Interrogation and Display System and X-Monitor provide real-time monitoring of data in various text and graphical formats. X-Capture and X-Local Recording Capability are used to record simulation data for posttest analysis and plotting. Posttest analysis and plotting are accomplished with X-Auto Analysis and X-Plot tools.

The CAST capability allows monitoring of simulation data and MIL-STD-1553B data buses. MIL-STD-1553B data can be acquired through any computer containing a VME backplane. For the X-31 simulation, the MIL-STD-1553B boards reside in a VME card cage, which is connected through the UMN to a monitoring computer, Fig. 2. The real-time monitoring program links to the UMN data through a set of software toolkit functions. The user is able to select the desired parameters from any MIL-STD-1553B data bus, and from the simulation in real time. X-Monitor provides the user with real-time graphical displays of the test data. The X-Aircraft Interrogation and Display System was designed to provide interrogation of FCS data and perform real-time logic functions. It is used to determine whether the control logic software is functioning properly.[6]

In addition to the comprehensive monitoring capability, two data recording methods are available to the users. X-Capture captures real-time data from the simulation computer and MIL-STD-1553B data buses into CAST workstation memory. The captured data can be plotted immediately for verification of test status or saved for later processing. Data captured this way are limited to short runs of several minutes. X-Local Recording Capability is a utility designed to control the local recording capability that runs on the Encore computers. X-Local Recording Capability can record all simulation and MIL-STD-1553B data for up to an hour, making it extremely useful in troubleshooting intermittent failures.

X-Auto Analysis analyzes test data in interactive and batch modes. It provides two different types of analysis: time history comparisons and frequency response analysis. Time history comparisons include statistical tests for minimum and maximum differences and root-mean-square error, and a custom routine that checks the closeness of two data sets against a user-specified tolerance. Frequency analysis is performed using fast Fourier transforms to give amplitude, phase, and coherence plots.

X-Plot is a plotting application that graphs time histories, frequency responses, and x-y plots. X-Plot also can be used in interactive or batch modes. Some X-Plot features include application of basic mathematical functions to any signal, renaming a signal, scaling the axes, and switching between linear and log scale.

These CAST tools have effectively supported the F-18 and X-31 projects, providing rapid development of the simulations and reducing the time needed to verify new FCS software releases. Written in C language with Xlib interfaces, these tools have been easily customized to the needs of a project.

Visual System Approach

The visual system requirements for the X-31 program include the need to provide out-the-window-scenes and simulated HUDs for pilot training and mission planning. To visualize aircraft motion at high angles of attack, flight control engineers require a three-dimensional (3-D) dynamic model of the aircraft with moving control surfaces and thrust vectoring paddles. Out-the-window scene performance requirements are the most critical. Refresh rates of 30 Hz and time delays from pilot input to scene update of less than 80 msec are required. The 3-D dynamic model is not used by the pilot to close the control loop, hence lower update rates are acceptable. Smooth motion at the 15-Hz refresh rate has proven adequate. A typical out-the-window scene is shown in Fig. 8 and the 3-D dynamic model is shown in Fig. 9. The arrow coming from the middle of the aircraft is the velocity vector. The vertical angle represents angle of attack, the horizontal angle represents angle of sideslip. The design approach to meet the rapid X-31 simulation development uses low-cost visual hardware and commercial modeling and display software.

The hardware and software approach to visual system development for the X-31 simulation was developed over the past three years on the X-29 Forward-Swept Wing and F-18 High Alpha Research Vehicle Programs. The hardware platform used is the Silicon Graphics Power Series 4D-440 with the VGX graphics option, which is needed to meet the refresh and scene complexity requirements. The software approach uses commercial development tools that allow reusing visual scene databases previously generated at the NASA Ames Research Center. This approach saved several man-years of effort by using databases generated for the flight test range at Edwards, California. The database conversions and subsequent modifications are performed using Multigen® software. The real-time scene generation and display of the databases is performed by Generic Visual System™ software. All 3-D models have moving control surfaces and were built using Multigen software. The 3-D models also run under the Generic Visual System software.

The approach described previously has proven very effective in meeting the rapid development requirements of the X-31 simulation. In the research environment, the ability to quickly respond to new requirements for visualizing simulation and flight data is critical. The software tools allowed someone with no previous visual system training to develop the complex X-31 aircraft model within weeks. The model includes moving control surfaces, landing gear, and thrust vectoring paddles.

Summary of Results

The development of the X-31 simulation was accomplished in record-time. Figure 10 summarizes the major areas where improvement in the development effort was made. It is difficult to compare other simulation developments to the X-31 simulation because of varying degrees of code availability and model complexity. However, the figure provides a rough estimate of the

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™Generic Visual System is a trademark of the Gemini Corp., Irvine, California.

time saved by using the X-31 productivity tools. All figures are normalized to one. The first entry is the effort required to develop the aerodynamic table look-up routines. The Look-Up Code Generator was the main contributor to the efficiency gained in this area. The second entry is the time required to develop the batch simulation. The X-Plot program and command files resulted in the majority of the 80-percent savings in development time. The use of the FORTRAN control laws from MBB personnel also saved considerable time in creating the batch simulation. The third entry is for the RTADS. The savings in the RTADS schedule was a result of the two previously discussed savings. The RTADS schedule also benefited from the quick development of the cockpit, the electronic interfaces to the simulation, and the visual system.

Concluding Remarks

The rapid development of the X-31 simulation has met the requirements for flight test operations, and flight control software verification and validation using a flight control system hardware-in-the-loop simulation configuration. The batch simulation was operational in only 3 months, the real-time all-digital simulation was operational in just 6 months. The flight hardware-in-the-loop simulation was developed in less than 9 months.

The X-Window-based computer-aided system test tools saved more than 6 months of valuable development time. The tools helped engineers to automate test setup, data recording, real-time display, analysis and plotting of simulation runs. Aerodynamic tables were generated using a table look-up code generation tool to quickly develop the simulation. The large aerodynamic database of over 200,000 points was implemented and tested in only 2 workweeks.

The X-31 simulation system provides several advanced capabilities to the pilots and flight test engineers involved in the program. These capabilities include the three-dimensional aircraft model used to visualize aircraft motion, surface motion, and thrust vectoring action at high angles of attack. The X-31 simulation system comprises the latest in software and hardware technology integrated into a system that enhances the flight test operations of the program.

References

[1]Knox, Fred and Schellenger, Harvey, "X-31 Flight Test Update," AIAA-92-1035, Feb. 1992.

[2]Mackall, Dale, McBride, David, and Cohen, Dorothea, *Overview of the NASA Ames-Dryden Integrated Test Facility*, NASA TM-101720, 1990.

[3]Goossen, Emray, "Verification of Flight Critical Systems," SAE paper 901051, Apr. 1990.

[4]Dornheim, Michael A., "Low-Cost Simulation Likely to Reshape Market," *Aviation Week and Space Technology*, Sept. 2, 1991, vol. 135, no. 9, pp. 38–41.

[5]Evans, Martha B. and Schilling, Lawrence J., *The Role of Simulation in the Development and Flight Test of the HiMAT Vehicle*, NASA TM-84912, 1984.

[6]Glover, Richard D., *Design and Initial Application of Extended Aircraft Interrogation and Display System, Multiprocessing Ground Support Equipment for Digital Flight Systems*, NASA TM-86740, 1987.

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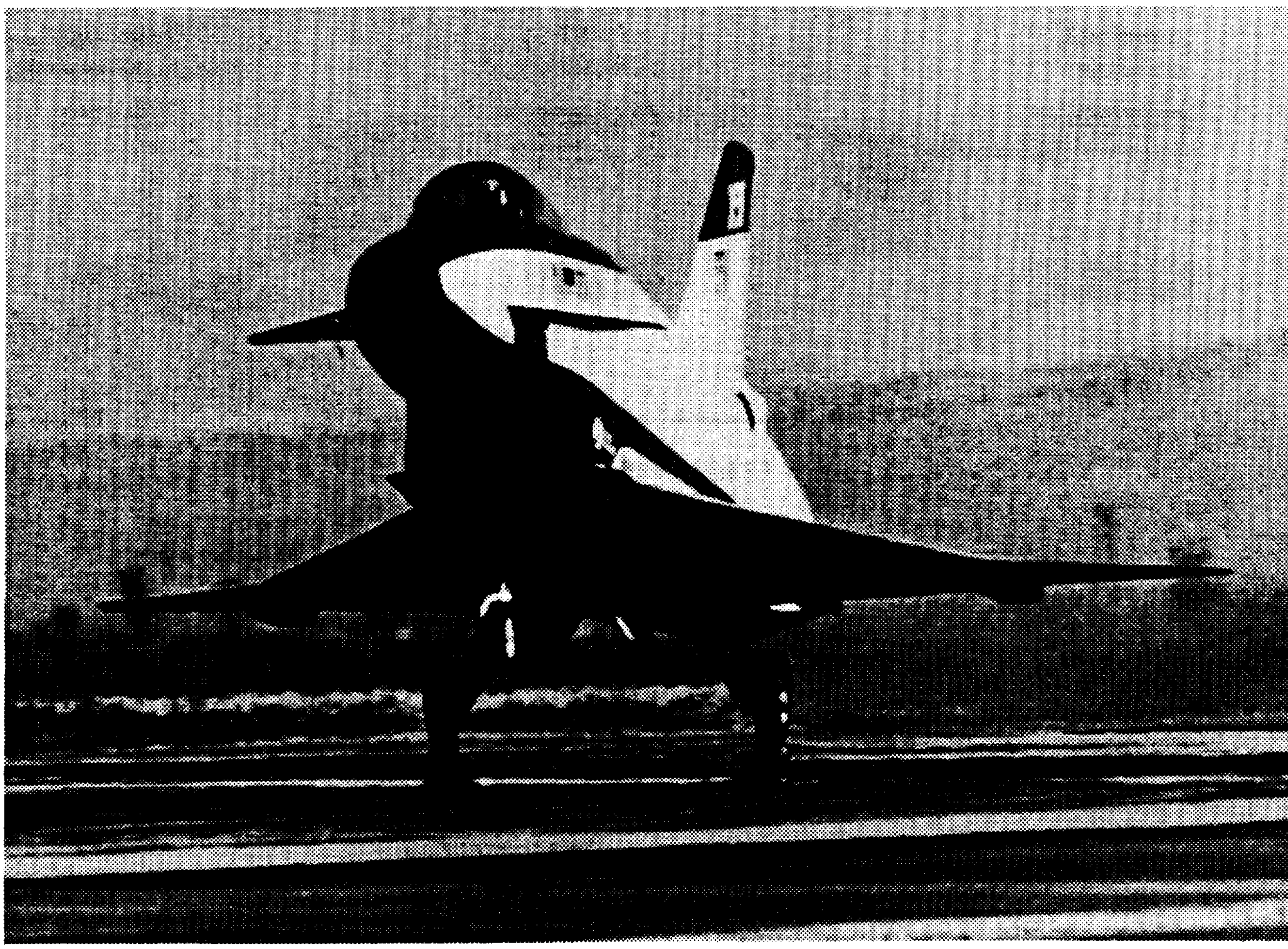

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Fig. 1 Enhanced Fighter Maneuverability Vehicle.

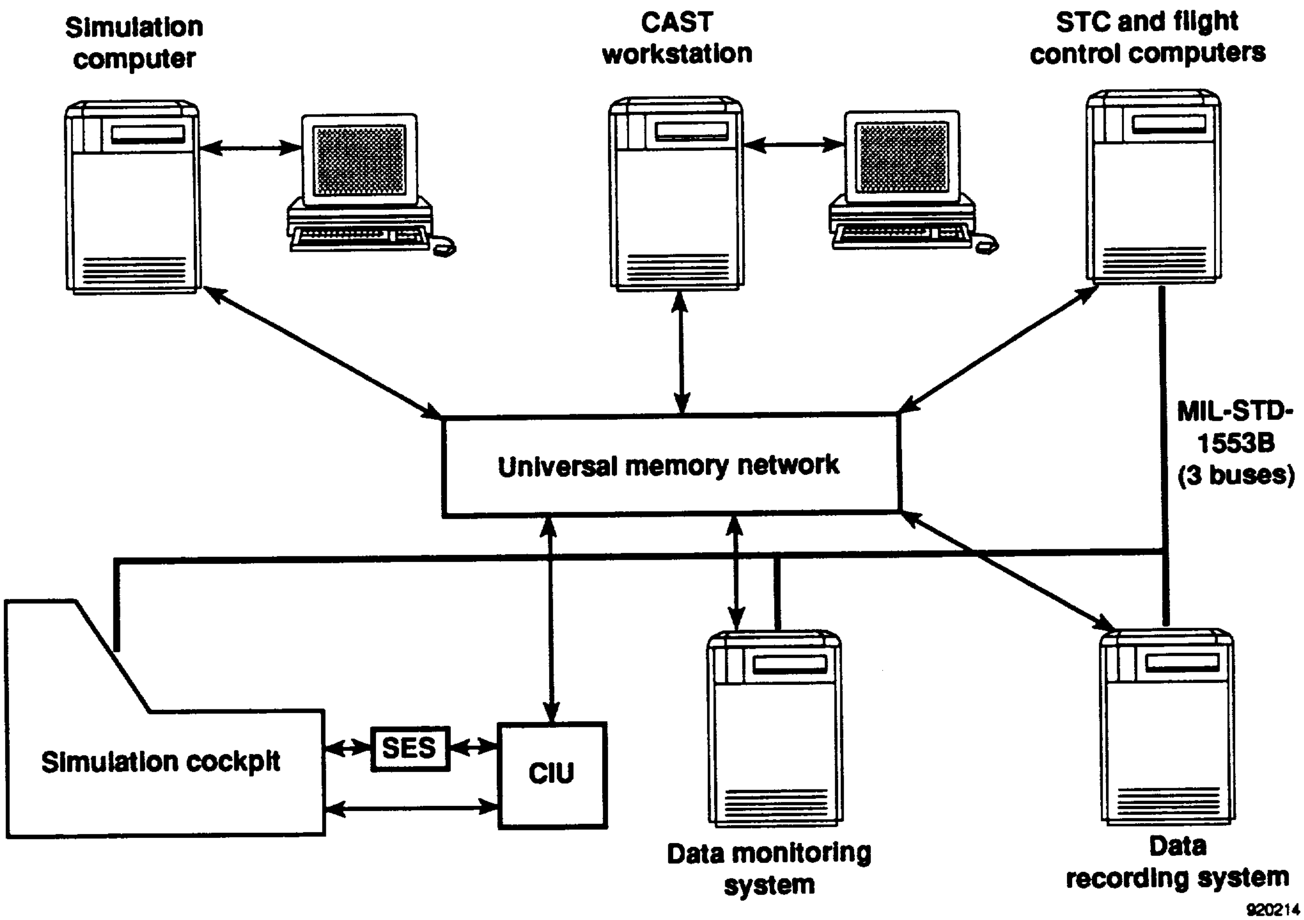

Fig. 2 X-31 simulation architecture.

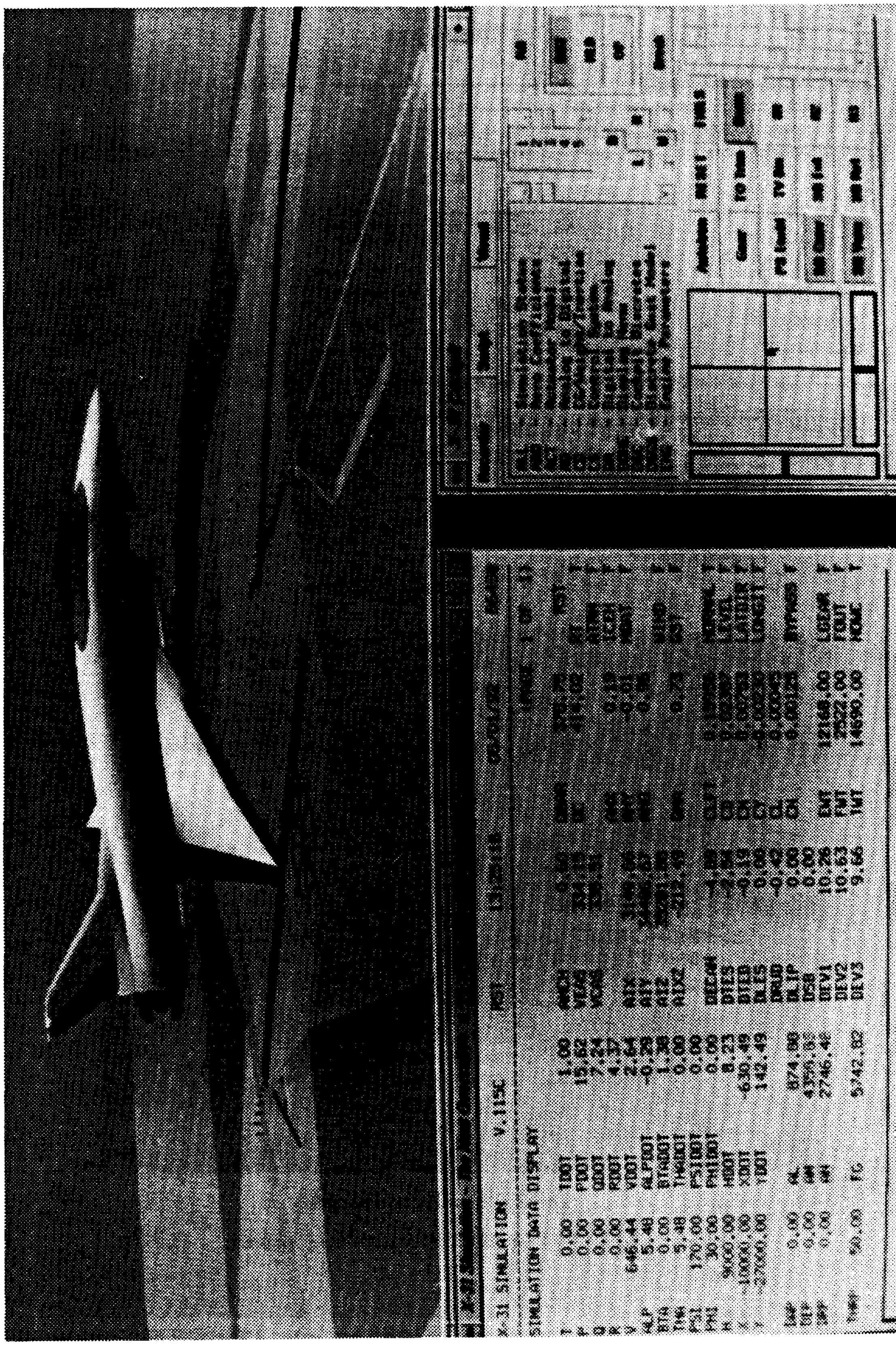

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Fig. 3 X-Window simulation displays used during development.

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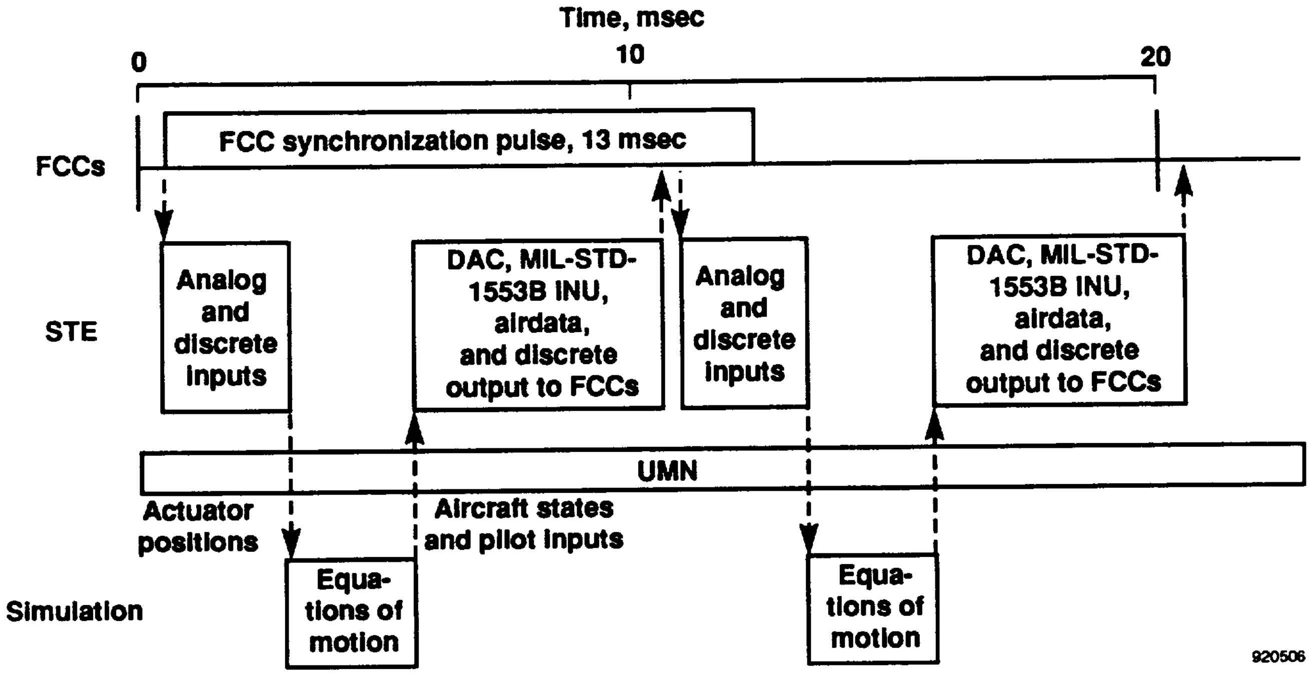
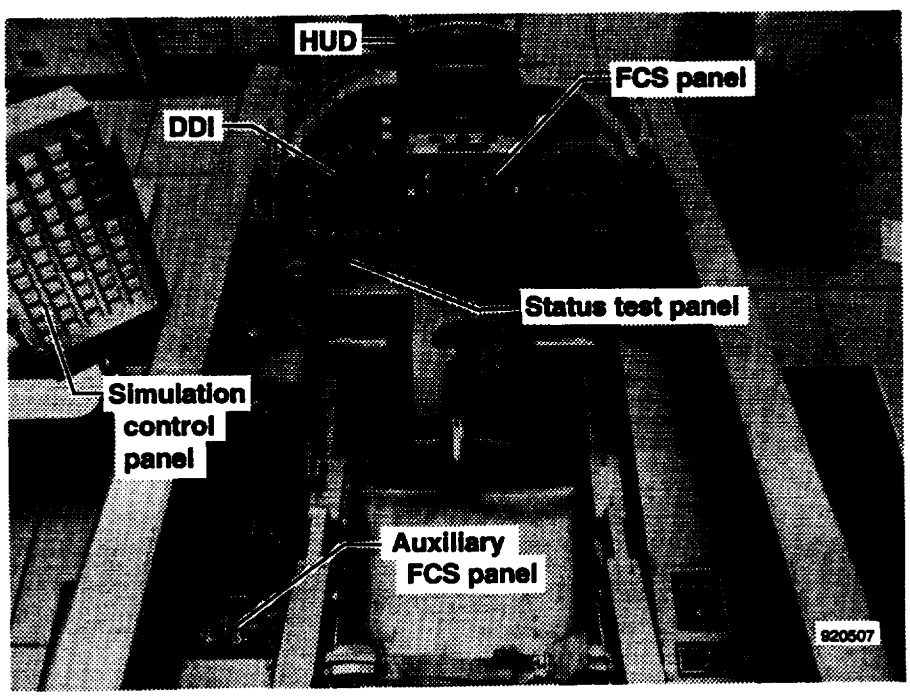


Fig. 4 Synchronization scheme.



(a) X-31 simulation cockpit.

Fig. 5 X-31 simulation and vehicle cockpits.

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(b) X-31 vehicle cockpit.

Fig. 5 Concluded.

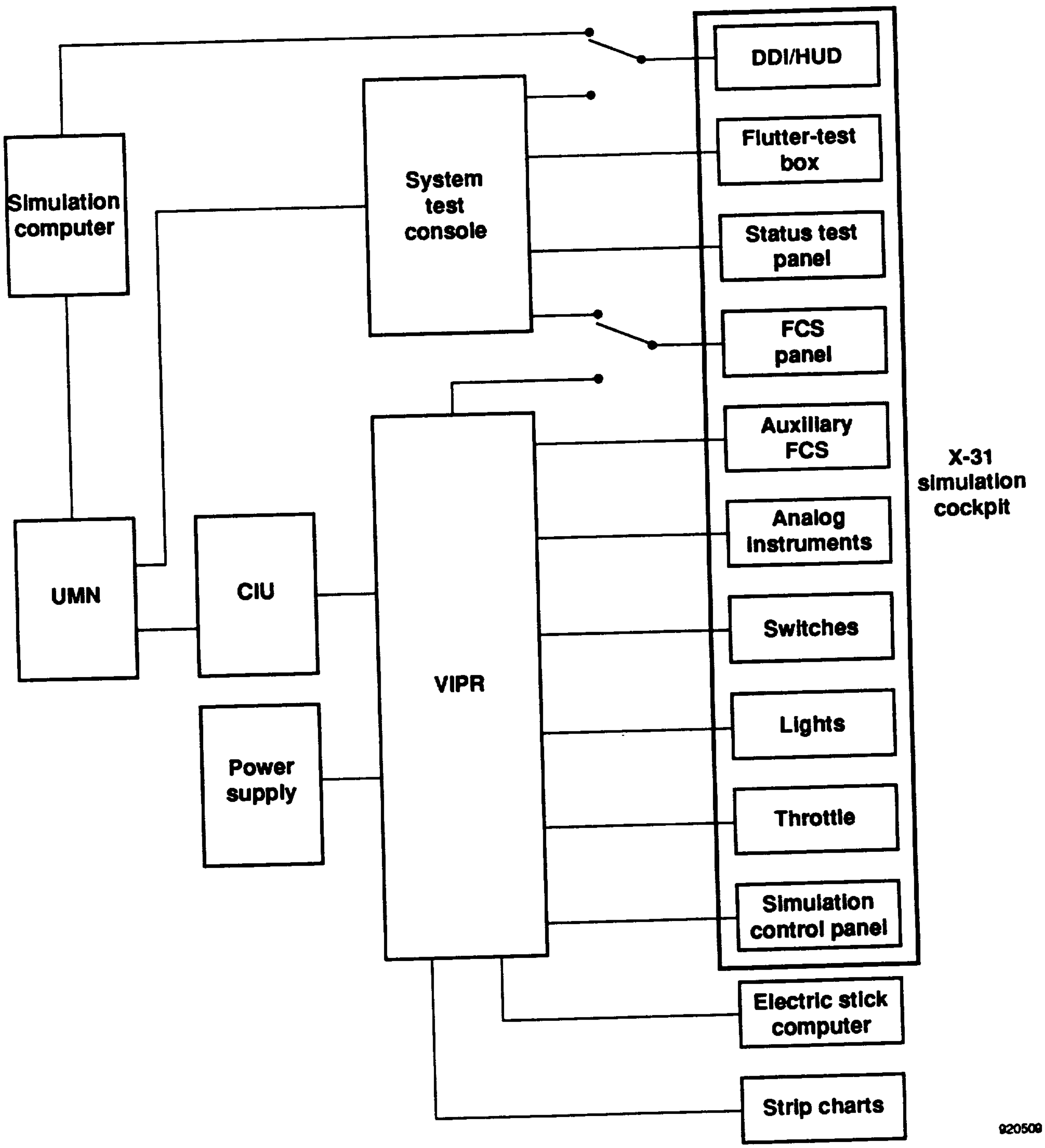

Fig. 6 Cockpit and simulation interfaces.

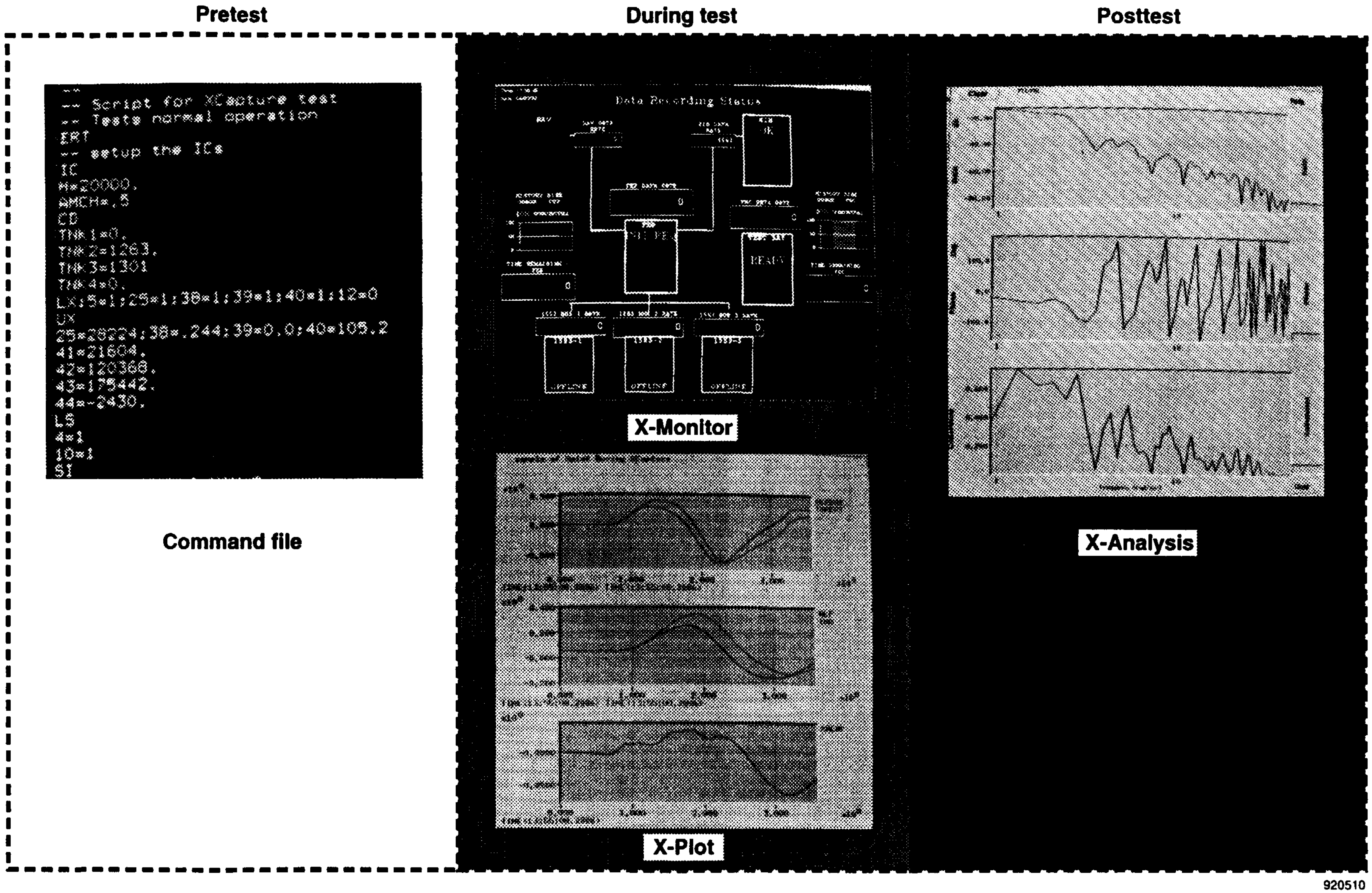

Fig. 7 CAST display.

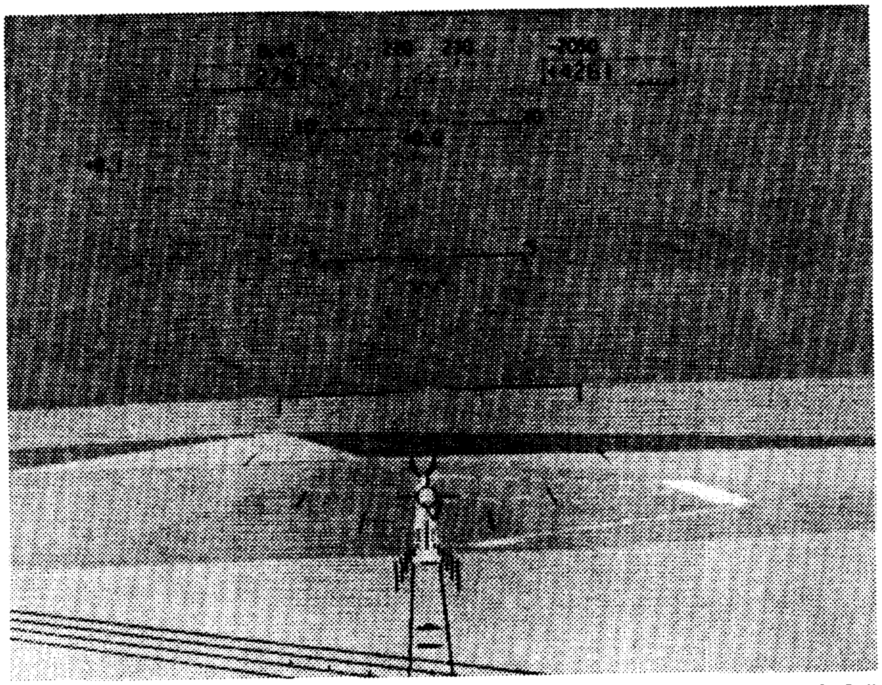

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Fig. 8 X-31 simulation out-the-window display of the Edwards area.

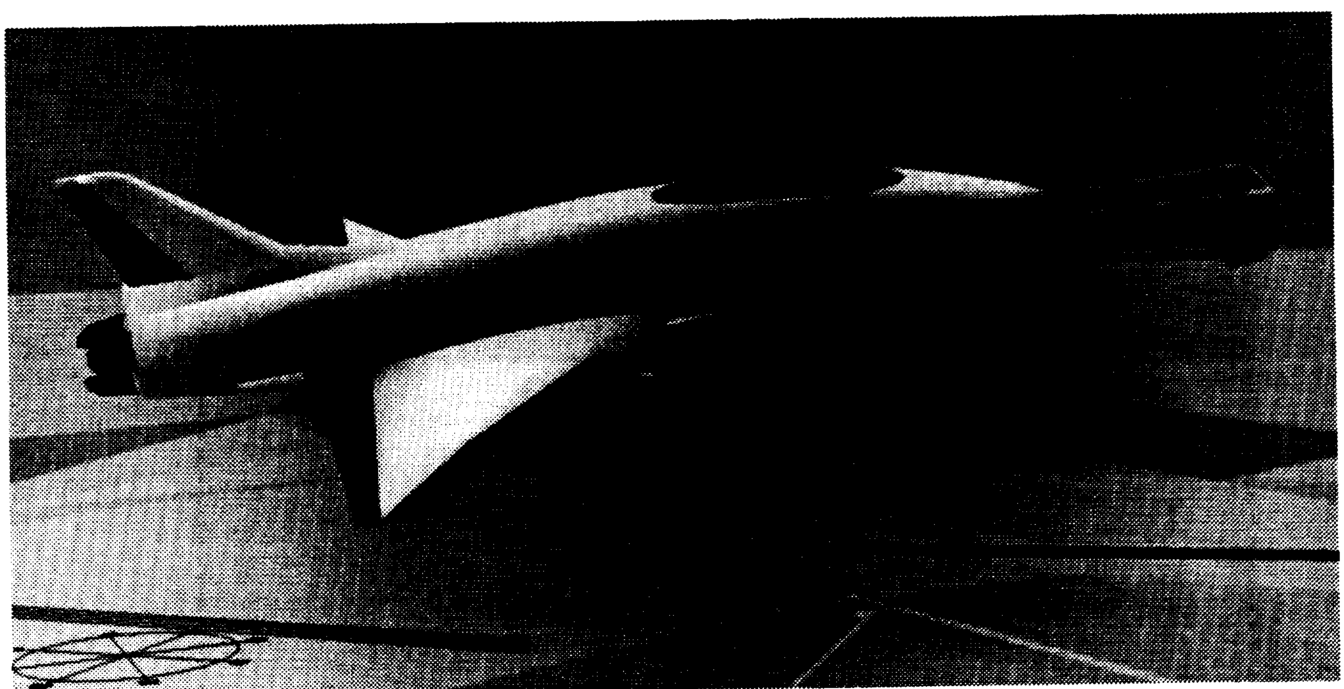

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Fig. 9 Dynamic 3-D model.

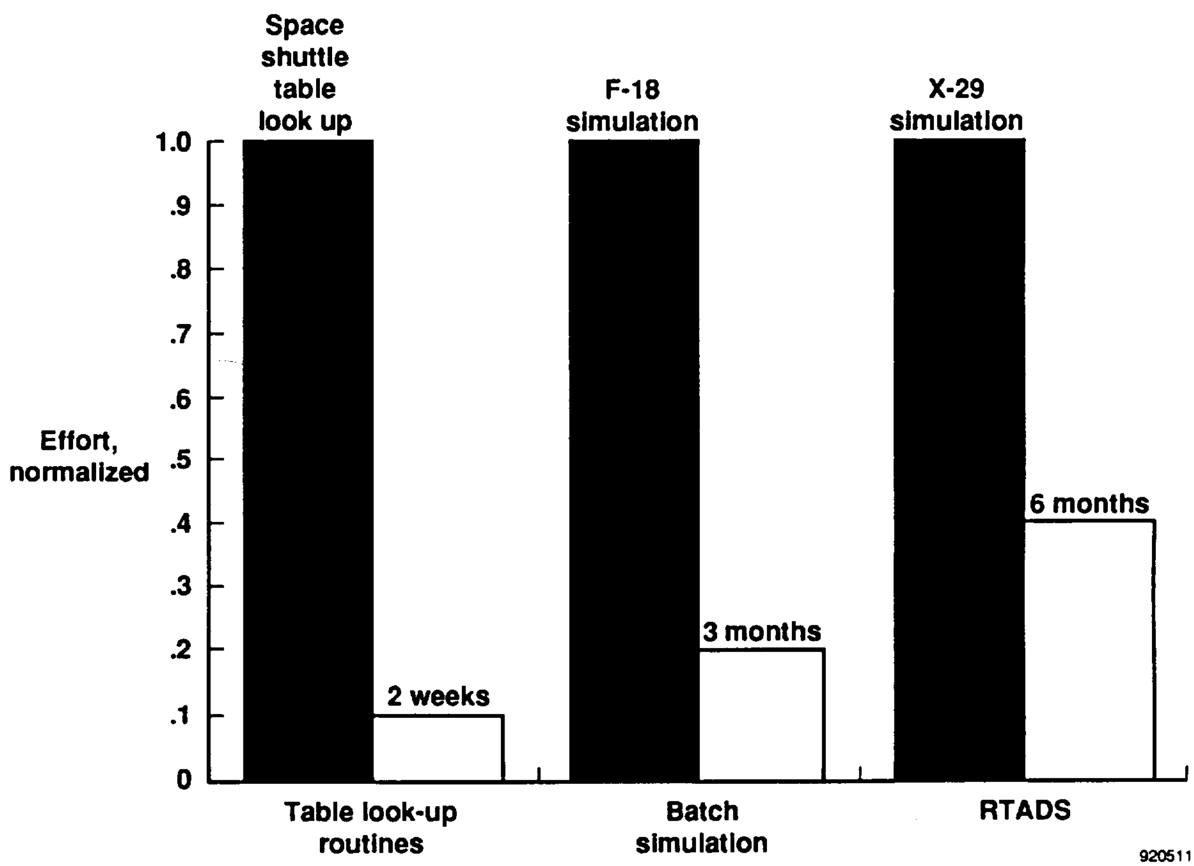

Fig. 10 Time savings in the X-31 simulation development.

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13. ABSTRACT *(Maximum 200 words)*

The X-31 Enhanced Fighter Maneuverability Program has been reorganized to form the International Test Organization, with the NASA Dryden Flight Research Facility (NASA-Dryden) as the responsible test organization. The two X-31 research aircraft and engineering support personnel have been colocated at NASA-Dryden, with flight test operations beginning in April 1992. Therefore rapid development of a hardware-in-the-loop simulation was needed to support the flight test operations at NASA-Dryden, and to perform verification and validation of flight control software. This paper will discuss the X-31 simulation system requirements, distributed simulation system architecture, simulation components from math models to the visual system, and the advanced capabilities the X-31 simulation provides. In addition, unique software tools and the methods used to rapidly develop this simulation system will be highlighted.

14. SUBJECT TERMS
Hardware-in-the-loop; Real-time simulation; Simulation cockpit; Verification and validation; Visual systems; X-31 Enhanced Fighter Maneuverability

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